

---

## **Identification of spatial hotspots for road safety improvement: Case of Northern Ireland.**

Bronagh Coll  
CenSSOR School of Mathematics and Physics, Queen's University Belfast

Salissou Moutari  
CenSSOR School of Mathematics and Physics, Queen's University Belfast

Adele H. Marshall  
CenSSOR School of Mathematics and Physics, Queen's University Belfast

### **Abstract**

In recent years, the concept of composite performance index, brought from economic and business statistics, has become increasingly used in the field of road safety. The construction of the composite safety performance index (CSPI) involves the following key steps: the selection of the most appropriate indicators to be aggregated and the method used to aggregate them. Over the last decade, various aggregation methods for estimating the CSPI have been suggested in the literature. However, recent studies indicate that most of these methods suffer from many deficiencies at both the theoretical and operational level; these include the correlation and compensability between indicators, as well as their high "degree of freedom" which enables one to readily manipulate them to produce desired outcomes [7], [8], [9]. In this study, we introduce an alternative non-linear aggregation method for the estimation of the CSPI, which is then used to identify and rank temporal and spatial hotspots for Northern Ireland. The obtained results highlight the stability and consistency of the proposed method, through a successful reduction in the deficiencies associated with traditional aggregation methods. Furthermore, the developed method can be viewed as an intelligent support system for road safety evaluation.

### **1. Introduction**

Due to the rapid growth in motorisation, road collisions are set to rise in the future unless timely and appropriate actions are taken to improve road safety [12]. Safety indicators are increasingly used to identify and combat the rising problems of road safety. In general terms, a road safety indicator is defined as a quantitative or qualitative measure derived by a series of observed facts relative to a particular collision [10]. Safety Indicators are advantageous in that they can display large amounts of information in a more simplified format. However, given the multitude of factors influencing road traffic collisions, it is somewhat difficult to assess indicators on an individual basis. Therefore, to facilitate decision making, it is often preferable to have the various indicators aggregated into a single composite index, also referred to as the road traffic Composite Safety Performance Index (CSPI) [10]. CSPIs are often used to analyse the current safety conditions of road traffic systems and assess their performance on an on-going basis and subsequently for benchmarking countries, regions etc. The key steps in the construction of the CSPI include: the selection of the road safety indicators to be aggregated and the choice of the method to be used to aggregate them. In recent years, various aggregation methods for the estimation of the CSPI have been suggested in the literature. These methods include: equal weighting, budget allocation, analytic hierarchy process, data envelopment analysis, principal component analysis, factor analysis, neural networks, grey Delphi method, and the fuzzy method, see [1], [2], [3], [4], [15], [16]. However, despite the significant research effort in the area, the theory of the aggregation of road safety indicators into CSPI is far from being complete. In fact, current aggregation methods used in the development of CSPI exhibit various deficiencies at both the theoretical and operational level [9]. These shortcomings include the correlation and compensability between indicators, strong reliance on expert opinions as well as their high "degree of freedom" which enables one to readily manipulate them to produce desired

---

---

outcomes [7], [8], [9]. The aim of this paper is to propose a new method for the construction of road traffic index, which strives to minimise the deficiencies inherent to the traditional weighting methods. The approach consists of the following key steps: the selection of the appropriate road safety indicators to be aggregated, the pairwise comparisons of indicators, and the development of the composite safety performance index, which will focus on quantitative uniformly measurable indicators.

The paper is organised as follows: Section 2 provides a brief overview of current aggregation methods used to estimate the CSPI, and discusses their relevance and limitations. Section 3 presents the methodology advocated in this study including the structure of the road safety adopted, the main conceptual framework and the rationale behind the new approach, and the corresponding algorithmic steps and the selection of appropriate road safety indicators. Section 4 is dedicated to the implementation and the application of the introduced method to identify and rank spatial hotspots for Northern Ireland, as well as the discussion of the results. Finally, Section 5 concludes the paper and outline further works.

## 2. Background

Over the last decade, a wide variety of aggregation methods for estimating the CSPI have been suggested in the literature. These methods are essentially based on the following principle: allocating weights to individual indicators and then aggregating them to form the CSPI. As no widely agreed method exists on the aggregation, the choice of the aggregation method is merely based on the type of individual indicators and the researchers' preference [10]. Some of the commonly used aggregation methods include: equal weighting, budget allocation, analytic hierarchy process (AHP), data envelopment analysis (DEA), principal component analysis (PCA) and factor analysis (FA).

Equal weighting is the most basic aggregation technique, which simply consists of placing equal weights on individual indicators, and averaging them to get the CSPI. Although this method is very straightforward and easy to implement, its major shortcoming is its assumption of equal importance of indicators, while in reality they contribute to road safety in varying degrees. Budget Allocation method is an aggregation technique where experts are given a budget of  $N$  points to be distributed over a number of indicators, allocating more points to those indicators for which they want to stress their importance. The points allocated to each indicator will form its weight, and the CSPI is given by the weighted average of the indicators. AHP method also incorporates expert opinions. It is based on the decomposition of a complex problem into a hierarchy and ensures that both quantitative and qualitative aspects of the problem are incorporated into the evaluation process, during which weights of indicators are systematically extracted by means of pairwise comparisons [4], [15]. Then the CSPI is given by the weighted average of the indicators. DEA method differs slightly from the previous methods, since it is based on a linear programming method. The weights of the indicators are given by the solution of the linear programme and the CSPI is given by the weighted average of the indicators. Although basic DEA model enables the estimation of weights without the use of experts' opinions, adapted DEA models use constraints which require limits or ranges which are solely based on expert opinions, thus making the model more subjective leading to inconsistencies in results. Moreover, constraints in the DEA model can combine indicators, which may not be directly linked to the phenomenon being measured. PCA is a multivariate statistical procedure, which aims to reduce a large set of variables to a small set of variables whilst still retaining most of the information. The central concept of PCA is based on an orthogonal linear transformation to convert a set of possible correlated variables into a set of linearly uncorrelated variables, referred to as principal components [4]. FA is very similar to PCA and it is used to investigate whether a number of variables (indicators) of interest are linearly related to a smaller set of unobservable factors. Although PCA and FA can be useful for gaining insight into the underlying structure of a dataset, e.g. grouping individual indicators according to their degree of correlation, the major issue with these approaches is that they estimate weights based on correlations which may not be directly linked to the phenomena being measured [4]. Additionally, these methods are sensitive to outliers in the data and require large sample datasets; however in the field of road safety analysis these requirements are not always fulfilled.

---

In recent years, many attempts have been made to introduce new approaches to address the limitations of the aforementioned methods. These include fuzzy comprehensive assessment method [3], neural networks [15], grey Delphi method [6], hierarchical fuzzy TOPSIS method [1] etc. However, most of these attempts still do not address the major criticism on the relevance of the obtained CSPI, which is viewed as a result of an arbitrary weighting and combination of the indicators [8, 9]. Indeed most of the aggregation methods generally combine road safety indicators without consideration of the underlying relationship between these indicators, the measurement unit, as well as the degree of non-compensability between individual indicators [9].

### 3. Methodology

One of the main challenges in the development of the CSPI lies in the identification of the appropriate observable indicators/variables to be used in describing the traffic safety system, as well as the selection of the most appropriate aggregation method. Given that without road traffic collisions, the field of road safety analysis would be probably irrelevant, then the central indicator for any sound road safety assessment will be the **number of collisions**. On the other hand, any other indicator can be cast as either the **potential cause** or the **consequence** of a road traffic collision, or the potential contributing factor of a consequence resulting from the occurrence of a road traffic collision. Thus, road safety is characterised by chains of facts, actions, causal relations and consequences in terms of human life and economic loss, and therefore it can be constructed around three main domains of indicator, as illustrated in Figure 1.

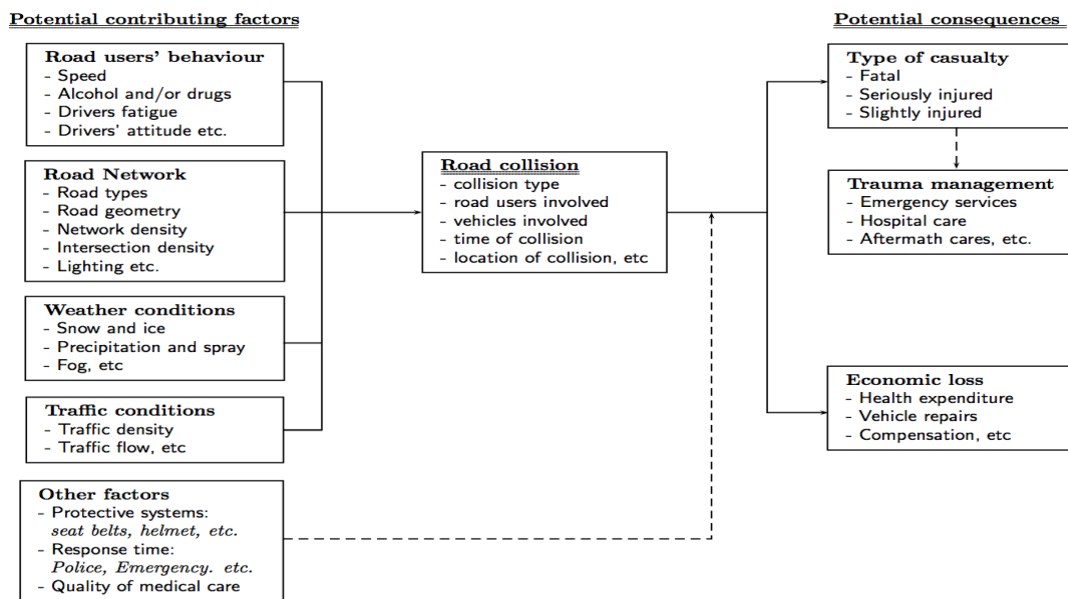


Figure 1 - Road Safety Structure.

#### 3.1 Conceptual framework

Suppose that we have  $n$  indicators denoted by  $I_j$ ,  $j = 1, \dots, n$ , and  $m$  realisations of each of these  $n$  indicators, then the data associated with these indicators can be summarised in the following  $m \times n$  matrix.

$$Y = \begin{pmatrix} y_{11} & y_{12} & \dots & y_{1j} & y_{12} & y_{1n} \\ \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\ y_{i1} & y_{i2} & \dots & y_{ij} & \dots & y_{in} \\ \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\ y_{m1} & y_{m2} & \dots & y_{mj} & \dots & y_{mn} \end{pmatrix}$$

where  $y_{ij}$  is the  $i^{th}$  realisation of the indicator  $j$ . Let  $\bar{Y} = \{\bar{y}_{ij}\}_{i=1, \dots, m, j=1, \dots, n}$  denote the normalised form of the matrix  $Y$ , such that for any given indicator, the components of the

corresponding column are defined in  $[0,1]$ , where 0 and 1 correspond to the lowest and highest value, respectively.

**Definition 1.** We call road safety performance index a measure defined in  $[0,1]$ , where 0 and 1 corresponds to the worst and best safety performance, respectively.

**Definition 2.** Let  $I_k$  and  $I_l$  be two given indicators. We say that  $I_k$  and  $I_l$  are comparable if there exists a pre-order relation between these two indicators in the following sense: an occurrence of one of the indicators may result in an occurrence of the other.

**Definition 3.** Let  $\Phi$  denotes the set of pairs of comparable indicators, and let  $(I_k, I_l) \in \Phi$ . Then, we said that  $I_k$  dominates  $I_l$ , and write  $I_l < I_k$ , if an occurrence of indicator  $I_k$  has most negative impact on road safety than an occurrence of indicator  $I_l$ .

**Definition 4.** Let  $\Phi$  denotes the set of pairs of comparable indicators. Let  $(I_k, I_l) \in \Phi$ , and let  $\Phi_{kl} \subset \Phi$  be the set of pairs of indicators which are conditionally comparable with the pair  $(I_k, I_l)$ . Then, the marginal safety performance index is defined by non-linear monotonic continuous function.

$$\begin{aligned} f_{kl}: [0, 1]^2 &\rightarrow [0, 1] \\ (\bar{y}_{ik}, \bar{y}_{il}) &\mapsto f_{kl}(\bar{y}_{ik}, \bar{y}_{il}), \quad i = 1, \dots, m, \end{aligned} \quad (1)$$

such that

1. if  $\Phi_{kl} = \emptyset$  we have
  - (i)  $f_{k,l}(0,0) = 1, f_{k,l}(1,1) = 1,$
  - (ii)  $\forall \bar{x}, \bar{z} \in (0,1)^2, \bar{x} < \bar{z},$  we have  $1 > f_{kl}(\bar{x}, \bar{z}) > f_{kl}(\bar{z}, \bar{x}) > 0$  if and only if  $I_l < I_k$
2. if  $\Phi_{kl} \neq \emptyset$  we have
  - (i)  $f_{k,l}(0,0) = 1,$  if and only if  $(I_s, I_t) = (0,0), \forall (I_s, I_t) \in \Phi_{kl};$
  - (ii)  $f_{k,l}(1,1) = 0,$  if and only if  $(I_s, I_t) = (1,1), \forall (I_s, I_t) \in \Phi_{kl};$
  - (iii) for any given values of  $(I_s, I_t) \in \Phi_{kl}, \forall \bar{x}, \bar{z} \in (0,1)^2, \bar{x} < \bar{z},$  we have  $1 > f_{kl}(\bar{x}, \bar{z}) > f_{kl}(\bar{z}, \bar{x}) > 0$  if and only if  $I_l < I_k$

**Definition 5.** Consider  $n$  indicators  $I_j, j = 1, \dots, n,$  and  $m$  realisations of these indicators. Let  $\Phi$  be the set of comparable indicators, and let  $f_{k,l}$  denote the marginal safety performance function associated with any pair of comparable indicators  $(I_k, I_l) \in \Phi.$  then the composite safety performance index can be defined by a non-linear monotonic function.

$$\begin{aligned} g : [0,1]^n &\rightarrow [0,1] \\ (\bar{y}_{i1}, \bar{y}_{i2}, \dots, \bar{y}_{in}) &\mapsto g(\bar{y}_{i1}, \bar{y}_{i2}, \dots, \bar{y}_{in}), \quad i = 1, \dots, m, \end{aligned} \quad (2)$$

such that

- (i)  $g(0_{\mathbb{R}^n}) = 1,$  where  $0_{\mathbb{R}^n}$  is the  $n$  dimensional null vector;
- (ii)  $g(1_{\mathbb{R}^n}) = 0,$  where  $1_{\mathbb{R}^n}$  is the  $n$ -dimensional vector of one;
- (iii)  $\forall (I_k, I_l) \in \Phi, g(\bar{y}_{i1}, \bar{y}_{i2}, \dots, \bar{y}_{in})(e_k + e_l), \forall i = 1, \dots, m,$  where  $e_r$  is the  $n$ -dimensional unit column vector with 1 at  $r^{\text{th}}$  position, satisfies the conditions in Definition 4.

### 3.2 Data and selection of road safety indicators

This study is based on Northern Ireland road collision data, which are recorded by the police service and stored on the national database known as STATs19. The data consists of 82 variables, which are split into three main categories: collision, casualty and vehicle. The STATs19 system uses three-category classification for type of casualty: fatality, seriously injured and slightly injured [13]. Damage only collisions, collisions reported after a 30-day period from the date of collision and collisions that have occurred in car parks are excluded from the data. However, it still remains the most detailed, complete and reliable source of information on road collisions in the UK [5]. Road safety is a complex phenomenon including various known and unknown factors, controllable and uncontrollable parameters. Therefore, the selection of key road safety indicators can be delicate or even controversial [10]. For this reason, this study is restricted to some non-controversial road safety indicators, including:

the number of overall collisions ( $I_1$ ), the number of fatalities ( $I_2$ ), the number of vehicles involved in overall collisions ( $I_3$ ), the number of serious injuries ( $I_4$ ), the number of collisions without fatal and seriously injured casualties ( $I_5$ ), the number of vehicles involved in collisions without fatal and seriously injured casualties ( $I_6$ ).

### 3.3 Pairwise comparison of the selected road safety indicators

The construction of the CSPI depends not only on the selected indicators but should also take into consideration the underlying relationship between these indicators, including the measurement unit, as well as the degree of non-compensability between individual indicators through their hierarchical structure [9]. Let us denote by  $y_{i1}, y_{i2}, y_{i3}, y_{i4}, y_{i5}, y_{i6}$   $i = 1, \dots, m$ , the realisations of the six indicators identified in section 3.2, respectively. Hence the corresponding data matrix  $Y$  is a  $m$  by 6 matrix, where  $m$  is the number of realisations of each indicator. Since any collision must involve at least one vehicle, then the indicators  $I_1$  and  $I_2$  are comparable. Furthermore, since for any vehicle to be involved in a collision the collision has to happen then  $I_1$  and  $I_2$  are conditionally comparable. On the other hand, as an occurrence of fatal casualties may be accompanied with an occurrence of seriously injured casualties and vice-versa, then the indicators  $I_3$  and  $I_4$  are comparable. Furthermore, since an occurrence of a fatal or seriously injured casualty is conditional to the occurrence of a collision (more specifically a fatal or serious injury collision) as well as the number of vehicles involved in these collisions, then the pair  $(I_3, I_4)$  is conditionally comparable with the pair  $(I_1, I_2)$ . On the other hand  $I_5$  and  $I_6$  are subsets of  $I_1$  and  $I_2$ , respectively. Thus, thanks to these underlying relationships between some pairs of comparable indicators, the set of pairs of comparable indicators  $\Phi$  reduces to:

$$\Phi = \{(I_1, I_2), (I_3, I_4)\} \quad (3)$$

Therefore, only two marginal safety performance index functions are required for this study.

### 3.4 Marginal and composite safety performance functions

Since  $|\Phi| = 2$ , then two marginal safety performance index functions are required for this study. The marginal safety performance index for a given realisation  $(\bar{y}_{i1}, \bar{y}_{i2})$   $i = 1, \dots, m$ , of the pair  $(I_1, I_2)$ , needs to take into account not only the values of each indicator in this realisation but also the magnitude of the disparity between these values. Furthermore, thanks to the relation (4), the marginal safety performance index function for  $(I_1, I_2)$  is defined only for  $y_{i1} \leq y_{i2}$ . The marginal safety performance index function for the pair of indicators  $(I_1, I_2)$  is given by:

$$f : [0, 1]^2 \rightarrow [0, 1]$$

$$(x_1, x_2) \rightarrow \frac{c - 1 - x_1 x_2 (e^{x_1 - x_2} + e^{x_1 - x_2})}{(c - 1)(1 + x_1 x_2 (e^{x_1 - x_2} + e^{x_1 + x_2}))} H(x_2 - x_1) \quad (4)$$

Where

- $x_1$  and  $x_2$  denote the normalised realisation of indicators  $I_1$  and  $I_2$ , respectively.
- $c = (2 + e^2)$ , with  $e$  the Euler's number i.e.  $e \approx 2.71828$ .
- $H(\cdot)$  denotes the Heaviside function defined by  $H(z) = \begin{cases} 1 & \text{if } z \geq 0 \\ 0 & \text{if } z < 0. \end{cases}$

Although an occurrence of the pair of indicators  $(I_1, I_2)$  does not always result into an occurrence of fatal or seriously injured casualties, the occurrence of indicators  $I_3$  and  $I_4$  is conditional to the occurrence of  $(I_1, I_2)$  and  $(I_5, I_6)$ . Then the conditional marginal safety performance index function for the pair of indicators  $(I_3, I_4)$  is given by:

$$h : [0, 1]^2 \rightarrow [0, 1]$$

$$(x_3, x_4) \mapsto (U - L) \frac{2(c - e^{x_3 - x_4} + e^{x_3 - x_4})}{(c - 2)(e^{x_3 - x_4} + e^{x_3 - x_4})} + L \quad (5)$$

where

- $x_3, x_4$  denote the normalised realisations of indicators  $I_3$  and  $I_4$ , respectively.
- $L = f(x_1 x_2)$  and  $U = f(x_1 - x_5, x_2 - x_6)$ , with  $f(\cdot, \cdot)$  given by (4) and  $x_1, x_2, x_5$  and  $x_6$  are normalised realisations of indicators  $I_1, I_2, I_5, I_6$ , respectively.
- $c = (1 + e^2)$ , with  $e$  the Euler's number i.e.  $e \approx 2.71828$ .

For any given normalised realisation of indicators  $(I_1, I_2, I_3, I_4, I_5, I_6)$ , the composite safety performance index function is made up with the contribution of all the marginal safety performance functions which satisfy the conditions in Definition 4, and it is given by:

$$g : [0, 1]^6 \rightarrow [0, 1] \\ (x_1, x_2, x_3, x_4, x_5, x_6) \mapsto \varphi(1 - \mu_1, 1 - \mu_2), \quad (6)$$

where

$$\varphi(a, b) = \frac{2(c - e^{a-b} - e^{a+b})}{(c-2)(e^{a-b} - e^{a+b})}, \text{ with } c = (1 + e^2), \text{ } e \text{ being Euler's number i.e. } e \approx 2.71828.$$

$\mu_1 = h(x_3, x_4)$  given  $(x_1, x_2, x_5, x_6)$  with  $h(\cdot, \cdot)$  defined by (5) and  $x_1, x_2, x_3, x_4, x_5, x_6$  are the normalised realisations of indicators  $I_1, I_2, I_3, I_4, I_5, I_6$ ,

#### 4. Identification and ranking of spatial hotspots: Case of Northern Ireland

In this study, data associated with the six indicators, identified in section 3.2 for Northern Ireland (between January and December 2010), extracted from the STATS19 database were considered. For the spatial hotspots analysis we consider data associated with the six indicators from each of the 29 policing areas of Northern Ireland. To ensure that road safety resources are utilised efficiently and effectively, it is essential to use a consistent method in the construction of a road safety index. Therefore, an additional investigation of spatial hotspots is carried out after inclusion of a demographic factor, namely the population density (inhabitants per unit area).

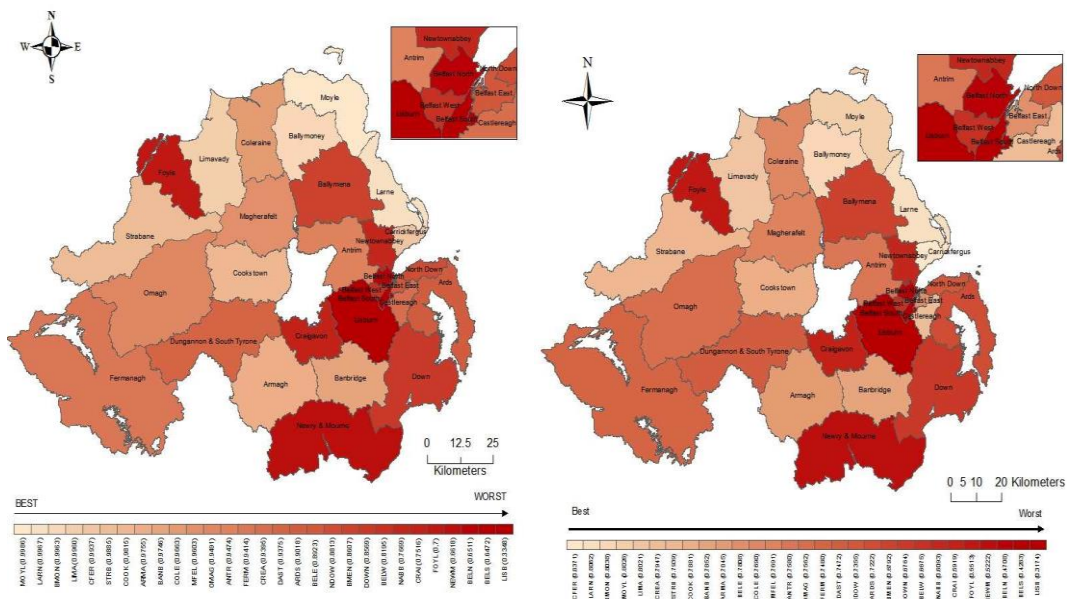
Using function (6), the CSPI corresponding to each policing area are estimated and presented in the column labelled "CSPI" in Table 1. Using the composite safety performance index CSPI, it appears that the "most underperforming" policing area, in terms of road safety, in Northern Ireland in 2010, is Lisburn (LISB), whereas the "best performing" policing area is Moyle (MOYL). However, for a more consistent spatial hotspots analysis, it is essential to include some demographic factors. After the inclusion of the population density of each policing area, we obtain a new composite safety performance index denoted CPSI\*. Using this new composite safety performance index, Lisburn (LISB) still remains the "most underperforming" policing area, in terms of road safety in Northern Ireland in 2010 whereas Moyle (MOYL) lost three places since the "best performing" policing area is now Carrickfergus (CFER). Furthermore, approximately half of the ranking positions given previously by CSPI have been affected by the inclusion of the population densities.

The method introduced in this study recognises the interconnections and nuances between individual road safety indicators in order to minimise the potential risk of under/over estimation. To illustrate this, let's consider the ranking position of Banbridge (BANB) and North Belfast (BELN) in Table 1. Column labelled  $I_3$  and  $I_4$  contain the number of fatal and seriously injured casualties, respectively. Both policing areas have 2 fatalities, and Banbridge (BANB) has an additional seriously injured casualty. Therefore, by ranking policing areas based only on the combined number of fatalities and seriously injured casualties, BANB would be labelled as "higher risk" than North Belfast (BELN). From Table 1, North Belfast (BELN) has approximately three times more collisions and vehicles involved in collisions than Banbridge (BANB), which significantly alters the ranking positions of the policing areas. These examples demonstrate the importance of examining the interconnections between indicators in the construction of a road safety performance index, and highlight the impact on the ranking positions if such relationships are ignored. It is clear that, analysing the connections between indicators can help differentiate between rare events (e.g. a bus crash killing 10 people) and likely events (e.g. a crash involving 2 cars with 2 fatalities), and the introduced method encompasses this fact through the relationships

between the severity of casualties, the number of collisions and the number of vehicles involved in the collisions.

Policing Area	I <sub>1</sub>	I <sub>2</sub>	I <sub>3</sub>	I <sub>4</sub>	I <sub>5</sub>	I <sub>6</sub>	Population Density	CSPI	Ranking CSPI	CSPI*	Ranking CSPI*
ANTR	184	349	2	16	167	317	93.86	0.9474	17	0.7580	16
ARMA	133	225	1	27	110	184	88.64	0.9755	22	0.7845	20
BELE	241	481	0	12	229	463	2341.57	0.8923	12	0.7808	19
BELS	379	685	1	31	347	638	2838.44	0.6472	2	0.4283	2
BMEN	216	393	1	46	176	325	100.39	0.8607	10	0.6792	10
CFER	96	192	0	15	81	168	490.66	0.9937	25	0.8371	29
COOK	133	236	1	19	116	203	58.89	0.9815	23	0.7881	22
CREA	188	373	1	21	169	337	778.32	0.9395	15	0.7947	24
DOWN	211	370	4	46	175	310	109.35	0.8569	9	0.6764	9
FOYL	321	602	3	34	290	551	283.56	0.7000	5	0.5513	5
LIMA	88	165	0	14	78	147	57.32	0.9960	26	0.8021	25
MFEL	111	212	3	44	77	153	78.09	0.960	19	0.7691	17
NABB	264	483	4	44	227	427	555.28	0.7669	7	0.6093	7
NEWM	292	539	4	58	241	454	110.68	0.6618	4	0.5222	4
STRB	93	164	2	23	72	134	46.54	0.9885	25	0.7939	23
ARDS	219	398	1	29	192	352	208.00	0.9018	13	0.7222	11
BANB	131	215	2	27	105	178	105.95	0.9746	21	0.7852	21
BELN	364	719	2	26	337	673	2003.07	0.6511	3	0.4708	3
BELW	258	489	1	35	230	448	2435.39	0.8195	8	0.6675	8
BMON	67	126	1	13	53	99	73.09	0.9963	27	0.8038	27
COLE	146	274	0	29	120	225	116.97	0.9663	20	0.7780	18
CRAI	258	481	3	53	212	399	247.40	0.7516	6	0.5919	6
DAST	164	286	2	38	136	240	73.70	0.9375	14	0.7472	13
FERM	172	278	4	30	146	245	33.63	0.9414	16	0.7480	14
LARN	76	138	0	16	64	121	94.29	0.9967	28	0.7480	28
LISB	423	780	8	73	360	678	263.71	0.3348	1	0.3174	1
MOYL	43	71	1	13	33	54	34.40	0.9986	29	0.8026	26
NDOW	235	437	0	30	211	394	980.93	0.8813	11	0.7355	12
OMAG	160	281	3	30	1350	237	46.77	0.9491	18	0.7562	15

**Table 1** –Spatial hotspot analysis. The first six columns contain data of the six road safety indicators for each of the 29 policing areas of Northern Ireland between (January and December 2010).



**Figure 2** - Spatial hotspots representation: CSPI - the composite index without including the population density (left). CSPI\* - the composite index after inclusion of the population density as an additional indicator (right).

## 5. Conclusions

This paper has introduced an alternative aggregation approach for the estimation of a composite road safety index, which is free from the major deficiencies of current methods, suggested in the literature. Based on the results from this study, further analysis could be done to examine the possible main causes of road collisions associated with these hotspots and conclude whether appropriate road safety interventions have been put in place whilst monitoring their efficiency and effectiveness over time. In the current political and administrative climate, the road safety decision-making process often demands a system of local evidence and feedback before countermeasures are deemed effective [11]. The method introduced in this study can be viewed as an intelligent decision support system for road safety performance evaluation, which could facilitate this process by enabling local authorities to measure the effectiveness of certain road safety measures over time and prioritise interventions for road safety improvement. There are still issues to be resolved in the construction of the CSPI. One important challenge is the ability to ascertain, and accurately measure, the most relevant road safety indicators to be used in the construction of the composite road safety index. Future research must recognise the tradeoff between indicators, which provide the most information on the road safety scenario, and those that yield comparable outputs across the items of interests (e.g. area, time interval, countries etc.).

## References

- [1] Biao, Q., Ruan, D., Shen, Y., Hermans, E., Janssens, D., 2012. Improved hierarchical fuzzy TOPSIS for road safety performance evaluation. *Knowledge Based Systems*, 32, 84-90.
- [2] Gitelman, V., Doveh, E., Hakkert, S., 2010. Designing a composite road safety index, *Safety Science*, 48, 1212-1224.
- [3] He, S., Wei, A., Yu, D., Tan, Z., Wang, P., 2009. Analysis of time distribution in traffic accident based on fuzzy assessment method. *Second International conference on Intelligent Computation Technology and Automation*, 649-651.
- [4] Hermans, E., Van der Bossche F., Wets, G., 2008. Combining road safety information in a performance index, *Accident Analysis and Prevention*, 40, 1337-1344.
- [5] Lyons, R., Ward, H., Brunt, H., Macey, S., Thoreau, R., Bodger, O.G., Woodford, M., 2008. Using multiple datasets to understand trends in serious road traffic casualties, *Accident Analysis and Prevention*, 40, 1406-1410.
- [6] Constructing road safety performance indicators using Fuzzy Delphi Method and Grey Delphi Method, *Expert systems with applications*,
- [7] Munda, G. and Nardo, M. 2003. On the methodological foundations of composite indicators used for ranking countries. In *OECD/JRC Workshop on composite indicators of country performance*, Ispra, Italy, May 12.
- [8] Munda, G. and Nardo M., 2005. Constructing Consistent Composite Indicators: the Issue of Weights, *EUR 21834 EN*, Joint Research Centre, Ispra.
- [9] Munda, G. and Nardo, M., 2009. Non-Compensatory/Non-Linear Composite Indicators for Ranking Countries: A Defensible Setting, *Applied Economics*, 41(12), 1513-1523.
- [10] Nardo, M., Salisana, M., Saltelli, A., Tarantola, S., Hoffman, A., Giovannini, E., 2008. *Handbook on Constructing Composite Indicators: Methodology and User Guide*. Organization for Economic Co-operation and Development.
- [11] OECD 2012. *Sharing Road Safety: Developing an International Framework for Crash Modification Functions*, OECD Publishing. <http://dx.doi.org/10.1787/9789282103760-en>.
- [12] Peden, M., Scureld, R., Sleet, D., Mohan, D., Hyder, A., Jarawan, E., Mathers, C. (Eds.), 2004. *World Report on Road Traffic Injury Prevention*. World Health Organization, Geneva.
- [13] Police Service of Northern Ireland user guide to police recorded injury road traffic collisions statistics (2012) (NIRSA).
- [14] Saaty, T.L., 1980. *The Analytic Hierarchy Process, Planning, Priority Setting, Resource Allocation*. McGraw-Hill, New York.
- [15] Shen, Y., Li, T., Hermans, E., Ruan, D., Wets, G., Vanhoof, K., Brijs, T., 2010. A hybrid system of neural networks and rough sets for safety performance indicators, *Soft Computing*, 14, 1255-1263.
- [16] Shen, Y., Hermans, E., Brijs, T., Wets, G., Vanhoof, K., 2012. Road safety risk evaluation and target setting using data envelopment analysis and its extensions, *Accident Analysis and Prevention*, 48, 430-441.